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Dynamics of ripples superimposed on a sand ridge on a tideless shoreface

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Abstract

The presence of ripples superimposed on an active sand ridge is the most usual situation under low- to moderate-energy conditions in the wave-dominated, tideless Ebro Delta coast. Four types of small-scale bedforms were identified, from the critical threshold of sediment motion to wash-out conditions: (i) small undulations with η <0.5 cm and λ ~8 cm, formed as a precursor of wave ripples when the Shields parameter was just below the theoretical critical; (ii) 2D wave ripples with η=1.2 cm and λ=7-10 cm; (iii) mixed 2D/3D current-dominated ripples with a maximum of η ~1.5 cm and λ=10-15 cm; and (iv) 3D wave-current ripples with a maximum of η ~2.2 cm and λ=7-20 cm. Ripple degradation was observed to occur when the energy of the hydrodynamic regime increased (wash-out conditions) and under low-energy hydrodynamic conditions, when ripples progressively decayed mainly as a consequence of biological activity. The wave ripples were static, while the current-dominated ripples migrated towards the SE at a rate of ~10 cm/h.

The potential role of ripple migration as an additional long-term mechanism of sediment transport is addressed. On the Ebro Delta shoreface, 3D ripple migration follows the direction of sand ridge migration towards the SE. The respective migration rates and their differences in size support the hypothesis that a subordinate part of sand ridge migration can result from the contribution of ripple migration under low to moderate regimes, suggesting that in specific environments the dynamics of small-scale bedforms can play a subordinate but not negligible role in the evolution of larger bedforms.

Keywords: ripples, superimposed bedforms, sediment dynamics, bedform migration, inner shelf, Ebro Delta

1. Introduction

Small-scale bedforms such as ripples are ubiquitous morphological features in sandy coastal and shelf sea environments. They display typical wavelengths (λ) of ~0.05–0.5 m and heights (η) of ~0.01-0.1 m (e.g. Allen, 1968; Nielsen 1992). Ripples can be generated by wave-, current- or wave- and current-induced flows (Flemming, 1980) in intermediate flow conditions between the thresholds for grain movement and sheet flow (Dalrymple and Rhodes, 1995). Morphologically, ripples are generally characterized by a straight crest alignment (2D ripples) at low speeds or a sinuous, catenary, linguoid, sinuous or lunate crest alignment (3D ripples) at high speeds (Thorne et al., 2009). Ripple geometries can differ significantly under wave or current-dominated conditions: wave-generated ripples are typically symmetrical in shape and have rectilinear crestlines, while in unidirectional flows they are primarily asymmetric and show 3D morphological features. Wave ripples can also be dynamic bedforms that usually migrate downstream following the wave skewness (Allen, 1973; Gallagher et al., 1998; Crawford and Hay, 2001).

Accurate prediction of ripple geometry is crucial to the modelling of bottom boundary layer dynamics and sediment transport because the ripple development and variation in bed roughness directly control the magnitude of bed stress, skin-friction/form-drag partition, near-bed velocity structure, vertical profiles of suspended sediment concentration and bedload rates (Glenn and Grant, 1987; Grant and Madsen, 1979; Wiberg and Nelson, 1992; Li et al., 1996; Li and Amos, 1998). Equilibrium ripple predictors based on extensive laboratory and field datasets have recently been developed for waves (e.g. Soulsby et al., 2012; Nelson et al., 2013), currents (e.g. Soulsby et al., 2012; Bartholdy et al., 2015) and for combined waves and currents (e.g. Li and Amos, 1998; Soulsby et al., 2012). Under non-steady forcing conditions, active ripple patterns and geometrical characteristics continuously adjust or adapt according to changing hydrodynamic conditions (Traykovski et al., 1999). Equilibrium ripple predictors may not capture this adaptation process, resulting in limited prediction of ripple dimensions during morphodynamically active periods. To solve this issue, time-evolving (non-steady) ripple predictors have recently been suggested (Traykovski, 2007; Soulsby et al., 2012).

Ripples are frequently superimposed on larger-scale bedforms. The hierarchical nature of bedforms has long been recognized, with two, three or even four different scales of bedform often occurring in the same system (e.g. Venditti et al., 2005; Li and King, 2007). Experimental and field data show ripples and small dunes generally lying on the backs or stoss sides of larger bedforms, many of which grow through amalgamation of the smaller bedforms, and small embryonic bedforms continually form on the backs of larger ones (Allen, 1982; Gomez et al., 1989; Venditti et al., 2005; Reesink and Bridge, 2009, 2007; Naqshband et al., 2014). The size, shape and dynamism of the superimposed forms are a function of the relative position with respect to the host bedform, and the size, shape and dynamism of the host bedform are at least partially a function of the superimposed bedform size and dynamics. For example, Cataño-Lopera and García (2006) observed larger and slightly asymmetric ripples on the crest and smaller and slightly more symmetrical ripples on the trough, but smaller and very asymmetric ones between the crest and trough of the primary bedform. When superimposed ripples migrate and reach the crest of a host bedform, they affect the shape and migration rate of the larger-scale bedform on the lee side and influence the nature of sediment deposition (Reesink and Bridge, 2007). Under unidirectional flow, the superimposed bedforms travel faster than the host bedform and overtake it (Reesink and Bridge, 2007), although the number of superimposed bedforms decreases gradually with the increasing flow velocity (Reesink and Bridge, 2009). In general, both the ripples and the host bedforms migrate in the same direction as the wave/current propagation. Typical daily-averaged migration rates in shallow waters are about 24-80 cm, with specific migration episodes ranging from 0.1 to 2 cm/min, depending mainly on the cross-shore location and ripple dimensions (Traykovski et al., 1999; Doucette, 2002; Masselink et al., 2007). Increasing flow speed results in faster migration rates but smaller ripple dimensions (Cataño-Lopera and García, 2006). Ripple migration rates are of a similar order of magnitude when ripples are superimposed on larger bedforms as when they are lying on a flatbed, although ripple migration rates vary depending on the location relative to the host bedform, being slower over troughs and faster over crests (Cataño-Lopera and García, 2006).

Though the presence of ripples is recurrent in shallow environments and frequently superimposed on larger-scale bedforms, the contribution of ripples to the dynamics of larger bedforms is poorly understood. Therefore, obtaining detailed knowledge of small-scale processes is essential to interpret the larger-scale ones, because the dynamics of the two processes are somehow connected.

This study analyses small-scale bedforms lying superimposed on a sand ridge field on the shoreface of the Ebro Delta. The location of ripples in relation to the larger bedform corresponds to one end of a sand ridge with symmetric geometry lying on the outer part of the prodelta of the former Cape Tortosa river mouth at 13.3 m depth ((a) Ebro Delta location. (b) Subaerial Ebro Delta shaded-relief and bathymetric contours offshore with location of the sand ridge field in grey. Location of tripod, sediment sample and the Buda Island meteorological station). According to Guerrero et al. (2018), NW wind-induced currents are the main cause of sand ridge migration towards the SE, while waves propagated in the opposite direction may be the mechanism for reshaping these forms to more symmetrical morphologies. The development and dynamism of ripples under waves and/or currents and the feasibility of ripple migration as a potential contributor to sand ridge migration are analysed. In addition, the reliability of ripple predictors and sediment transport estimations is discussed.

2. Study area

The Ebro Delta is located off the coast of Spain in the NW of the Mediterranean and it is the third largest delta of the Mediterranean Sea ((a) Ebro Delta location. (b) Subaerial Ebro Delta shaded-relief and bathymetric contours offshore with a), with an emerged area of 325 km^2. The submerged surface (prodelta) covers an area of ~2300 km^2 of the continental shelf and extends alongshelf up to 110 km southwards from the present river mouth (Díaz et al., 1996). The Ebro Delta is located in a micro-tidal, wave-dominated coast with a maximum astronomical tidal range of 0.25 m. As the tidal currents are negligible, with very weak intensities, and are only detectable in the absence of waves and winds, the Mediterranean Sea is frequently considered a tideless sea (King and Williams, 1949). However, meteorological tides (storm surges) play an important role as they cause increases in sea level of up to ~1 m (Bolaños et al., 2009). This area is characterized by persistent strong, dry and usually cold Mistral winds that blow from the NW through the Ebro valley (onshore winds) in autumn and winter. The Mistral wind is channelized into a limited band influenced by the orography, forming a seaward wind jet that usually develops in a ~50-km-wide band offshore (Grifoll et al., 2016). The NW winds have a clear seasonal pattern, the most intense and persistent ones occurring in winter and autumn. However, in spring and summer, offshore winds can also reach high intensities (Cerralbo et al., 2015; Grifoll et al., 2016). The NW wind regime results in relatively small waves along the Ebro coast because of the short fetch (<50 km). On the other hand, the most intense swell-dominated storms come from the eastern sectors (E or ENE), where stronger winds coincide with a maximum fetch of approximately 700 km (Bolaños-Sanchez et al., 2007; Sánchez-Arcilla et al., 2008). These storms have an average duration of less than 24 h and typically occur more than 10 times per year, basically concentrated in the periods October-December and March-April (Sánchez-Arcilla et al., 2008). These eastern wave storms have an annual return period significant wave height () of 3.5 m (Bolaños et al., 2009).

Morphodynamics in the Ebro Delta nearshore are dominated by the easterly waves, which generate net alongshore currents directed towards the NW and SW at the north and south of Cape Tortosa, respectively (Jiménez and Sánchez-Arcilla, 1993). Small-scale bedforms (1 cm high and 8-14 cm apart) appear during fair-weather conditions at ~10 m depth on the shoreface of the Ebro Delta, with further vanishing because of seabed bioturbation (Guillén et al., 2008). At the study location, a sand ridge field has been identified lying over the former Cape Tortosa river mouth in the Ebro Delta (Guerrero et al. 2018). The sand ridge field extends between 5 and 15 m depth and has a maximum height and wavelength of approximately 2.5 and 400 m, respectively (Guerrero et al. 2018). The sand ridges are dynamic, with migration rates of ~10 m/y caused by SE-directed wind-induced currents.

3. Data acquisition, methodology and materials

This work is mainly based on field observations. Sediment samples, wind- and wave-field time series, and hydrodynamic and seafloor configuration measurements and observations (the latter obtained from a benthic tripod deployment) were used to analyse the small-scale sedimentary processes on the Ebro Delta shoreface. The data and the methodology used are explained in the following section.

3.1. Bottom sediment samples

Sediment samples were collected using a HAPS bottom core on the sand ridge field at the shoreface of the Ebro Delta (see location in (a) Ebro Delta location. (b) Subaerial Ebro Delta shaded-relief and bathymetric contours offshore with location of the sand ridge field in grey. Location of tripod, sediment sample and the Buda Island meteorological station b). The 13-cm-long core was sampled and analysed every centimetre. They were first dried in an oven at 80°C for 24 hours. The sediment fraction finer than 2000 μm was examined using an LA-950V2 laser scattering particle size distribution analyser (HORIBA), while the coarser fraction was sieved using a column with three sieves (6000, 4000 and 2000 μm). The grain size distribution and the median gain size (d_{50}) were estimated.

3.2. Winds and waves

Wind field measurements from the Buda Island meteorological station (latitude 40.707° N; longitude 0.834° E) were supplied by the Catalan Meteorological Service (SMC) (see location in (a) Ebro Delta location. (b) Subaerial Ebro Delta shaded-relief and bathymetric contours offshore with location of the sand ridge field in grey. Location of tripod, sediment sample and the Buda Island meteorological station b). The time series data provided wind speed intensities (gust velocity) and directions every 30 minutes. Wind data were obtained from the meteorological station located inland ~5 km to the west of the study area.

Wave field measurements and statistical data were obtained from the offshore buoy of Tarragona provided by the Spanish Ports Authority, with an hourly sampling interval (www.puertos.es). The buoy of Tarragona is located approximately 50 km to the east of the study area at 688 m water depth (latitude 40.680° N; longitude 1.47° E). From October to December 2013, when the strong, NW Mistral winds blew intensively, the Tarragona buoy measured high , mostly because of the long fetch. However, at the tripod location, the NW wind did not have sufficient fetch to develop large waves because it is very close to the coast. In fact, the former Cape Tortosa buoy had been recording wave field data for years and showed a blank region or a lack of waves in a window between 220° and 310° with respect to N (the former Cape Tortosa buoy was situated at 25 m water depth, relatively close to the tripod location).

Therefore, it was highly recommended to integrate wave field and wind conditions in a model able to transform waves, propagating them from the Tarragona buoy to the study area location but also generating and accounting for wind-induced waves from inland winds. To achieve this, the wave field data at the study site were obtained using the SWAN model by simulation of wave generation and propagation along the Ebro Delta shelf from 1 October to 31 December 2013.

The simulations were carried out with the SWAN Cycle III v. 41.20 model (Booij et al., 1999). The simulations were run using the standard values of all parameters recommended in the SWAN user manual. The wind forcing was considered throughout the entire domain to account for wave generation. The wave forcing was defined by the parametric wave spectra: the significant wave height (), the peak period (), the wave direction and the coefficient of directional spreading, interpreted as the directional standard deviation in degrees. The area of analysis comprised the continental shelf and shoreface of the Ebro Delta. The computational domain ranges from 311778 to 340000 m E and from 4494043 to 4521327 m N in UTM coordinates 31 N zone World Geodetic System (WGS-84). The bathymetry has a 90-m grid resolution and ranges from -100 m at the deepest outer region (E) to -5 m at the Ebro Delta (W). The bathymetric data were extracted from the Catalano-Balearic Sea bathymetric chart (Farrán, 2018). A uniform regular grid made up of more than 43000 computational cells was used (cell size: 140 x 140 m).

SWAN was run in stationary mode ($\partial N/\partial t = 0$) for hourly wind and wave conditions during the study period (October-December 2013), assuming that waves propagate instantaneously throughout the model domain with an immediate response to wind field changes.

3.3.Benthic tripod instrumentation

Instrumented bottom frames have been used since the 1960s to investigate bottom boundary layer processes and sediment dynamics without significant flow interference near the seafloor (Sternberg, 2005). Instruments attached to benthic tripod structures allow scientists to obtain measurements and observations of seabed micro-bathymetry, seafloor images, sediment characteristics, near-bottom hydrodynamics and suspended sediment concentrations.

An instrumented benthic tripod was deployed off Cape Tortosa on the Ebro Delta inner shelf over a sand ridge field at approximately 13 m water depth from 13 October to 31 December 2013 in the framework of the FORMED project ((a) Ebro Delta location. (b) Subaerial Ebro Delta shaded-relief and bathymetric contours offshore with location of the sand ridge field in grey. Location of tripod, sediment sample and the Buda Island meteorological station b).

The tripod stood ~2.50 m high and the feet formed an equilateral triangle of 3 m on each side, with weights at each foot to maintain stability (Image of the tripod structure during the deployment manoeuvres on the deck of the ship on 13 October 2013. Numbers indicate the position of the instruments used here: (1) video camera; (2) currentmeter; and (3) altimeter.). The frame was self-contained, fully submerged, and various batteries, instruments and dataloggers were attached to it. The instruments used measured current intensities and directions (currentmeter), turbidity (turbidimeters), direct seafloor images (video camera), and topographic seabed variability (altimeter). The basic instrument characteristics, location above the bottom (deck of the ship) and sampling strategy are shown in Image of the tripod structure during the deployment manoeuvres on the deck of the ship on 13 October 2013. Numbers indicate the position of the instruments used here: (1) video camera; (2) currentmeter; and (3) altimeter. and Technical characteristics and specifications of the instruments deployed on the Ebro Delta . The technical characteristics and set-up of the main instruments are described below.

An Aanderaa currentmeter (RCM-9) recorded the current intensity and direction at 0.94 m above the bottom (mab) every 30 minutes using an acoustic Doppler sensor emitting at 2 MHz and a magnetic compass (Technical characteristics and specifications of the instruments deployed on the Ebro Delta). The instrument was also equipped with a turbidity sensor that measured suspended sediment concentrations at 0.852 mab (Technical characteristics and specifications of the instruments deployed on the Ebro Delta).

An ALTUS altimeter measured the topographic variability of the seabed, with 2-mm resolution of changes in elevation of the seabed as the distance from an acoustic transducer located at 0.2 mab every 15 minutes (Technical characteristics and specifications of the instruments deployed on the Ebro Delta).

ALTUS operation is based on emitting a 2-MHz acoustic wave. The echo signal is filtered, amplified, rectified, and then compared with the programmed threshold to give a detection signal (Jestin et al., 1998). The altimeter time series was post-processed in order to automatically remove the spikes that appeared along the time series. The condition applied consisted in point-by-point comparison with the standard deviation of a 5-point window and substitution of the point with the previous one when it was greater than the deviation.

A GoPro Hero3 Black Edition version 1.1 recorded sequences of 10 seconds (s) every 4 hours (h) at 1.6 mab. The digital video camera provides oblique images at 12-120 frames per second (fps), with video effective pixels of 12 MP. Providing an oblique image, the camera has 1920x1080 resolution and micro HDMI with field-of-view modes. The seabed coverage was approximately 1.9 m^2.

Table I. Technical characteristics and specifications of the instruments deployed on the Ebro Delta tripod

Instruments	Measurement used	Sampling interval	Location
AANDERAA RCM-9	Horizontal current speed (cm/s) Current direction (Deg. M)	30 min	At 94 cmab
ALTUS 26001	Depth (m) Altitude (mm)	15 min	At 20 cmab
GoPro	Video images	10 s every 4 h	At 163 cmab

3.4. Time series data

Specific data quality controls were evaluated for each instrument and sensor following its own protocol and recommendations in order to assess the validity of the measurements. In addition, data were processed to obtain the desired variables as follows:

3.4.1. Ripple observations

Ripple geometry and dimensions are here described as the orientation of the crestlines, sinuosity and the cross-sectional ripple height and wavelength (η and λ, respectively).

The seabed morphology and evolution were analysed using images from the video sequences recorded with the digital video camera. The images provided a useful tool for identifying changes in seabed morphologies and particularly for identifying periods of ripple development. Seabed configurations were schematized and summarized over time. Periods with biological activity were also observed, although they were not included in the time series. About 18% of the video sequences (those classified as "no data") were of poor quality or unclear because of technical failures of the camera, high turbidity levels or biological activity that covered the visual field of the camera.

The altimeter provided direct information about the seabed variability as the distance from the transducer to the target or seafloor. Ripple heights were estimated from the topographic oscillations of the seabed level, recorded with the altimeter. The seabed position during each period of ripple formation was detrended using a polynomial fit to estimate ripple height from fluctuations of the bed elevations around a horizontal reference level. Then, ripple height was estimated statistically using the root mean square of the elevation multiplied by a factor equal to $2\sqrt{2}$. This is based on assuming a sinusoidal ripple cross section, since for a sine wave the height is equal to times the elevation of the standard deviation (Traykovski et al., 1999).

The instantaneous images were acquired from the videos and were first geometrically corrected using ground control points. Then, the ripple wavelengths were measured as the distance between successive ripple crests, mostly measured at the central areas of the images, where the resolutions as well as the deformations were optimum. In addition, box plots from the ripples crestlines in the images were used to distinguish and classify ripple geometries, specifically a box plot of the ripple crest directions and sinuosity index (length of ripples crest/length of rectilinear ripple crest, where 1 is straight rectilinear crests).

Migration rates were estimated as the time between the passing of two crests recorded with the altimeter. The ripple crests were first detected (applying a vertical threshold of 0.3 cm) and the distance between the two crests was assumed to be the time between the passing of a ripple crest. Then, the wavelength observed in the closest image to the altimeter observations divided by the time of a crest pass was used to estimate ripple migration.

3.4.2. Wave field time series

The wave field variables used here after the wave propagation explained above were , and wave direction (). The wind variables used were the maximum half-hourly gust velocity and the respective direction.

3.4.3. Wave orbital velocity

The wave orbital velocity was calculated following small-amplitude linear wave theory for regular waves. The orbital velocity just above the wave boundary layer over the bed due to monochromatic (single-frequency) wave height () and period () at water depth () is

.... (eq. 1)

where is the hyperbolic sine, is the wavenumber, is the wavelength, and and are the root mean square wave height and mean wave period, respectively (Soulsby, 2006). The was determined by applying the Newton-Rapshon iteration method to the dispersion equation following the algorithm of Fenton and McKee, (1990), which accounts for the effect of the currents and includes the wave-current angle correction. The wave-current angle is 0º when waves and currents are travelling in the same direction and 180° when they are travelling in opposite directions.

3.4.4. Bed roughness

For bed shear stress and sediment transport purposes, the estimated total roughness length was the sum of the grain-related or skin friction (), which is responsible for bedload transport (Soulsby 1997), and sediment transport components (related to the intensity of transport at very high flow speeds. The form-drag component, which is associated with turbulence that diffuses the suspended sediment up into the flow, was not considered. Thus,

.... (eq. 2)

where (Soulsby 1997)

.... (eq. 3)

.... for currents (eq. 4)

..........for waves (eq. 5)

and is the skin-friction shear stress according to Soulsby (1997), (kg/m^3) is the sediment density and (kg/m^3) is the water density.

3.4.5.Bed shear stress

The bed shear stress was calculated following the methodology proposed by Soulsby and Clarke (2005) and modified by Malarkey and Davies (2012) under combined waves and currents for hydrodynamic rough bed conditions and under the approximation of z_0 << BL << h, where BL is the wave boundary layer thickness and is the depth. The mean bed shear stress due to combined flow () over hydrodynamic rough beds (sand and gravel beds) is

.... (eq. 6)

where is the bed shear stress due to currents alone and is the bed shear stress due to waves alone. This variable was estimated considering the depth-averaged current speed as the current measured at the currentmeter depth and considering the bed roughness length of waves and currents estimated as explained above.

Finally, the maximum bed shear stress due to combined flow (Soulsby, 1997) is

.... (eq. 7)

where is the angle between the current and the wave travel direction.

3.4.6.Shields parameter and its thresholds

The Shields parameter (, also called the Shields criterion or number is a non-dimensional variable used to identify or determine when seabed states typically reach the initiation of sediment motion in a fluid flow (van Rijn, 2007a). The Shields parameter also gives an approximation of the boundaries or limits of seabed morpho-states in relation to the incident hydrodynamic conditions, in our case for a constant sediment size throughout the study period and evaluated during waves and currents separately (Soulsby et al., 2012).

.... (eq. 8)

The critical Shields parameter for initiation of motion is given as (Soulsby and Whitehouse 1997)

.... (eq. 9)

where is the critical threshold for the bed shear stress; is the dimensionless sediment size, with at the Ebro site; is the relative density; (m^2/s) is the kinematic viscosity coefficient; (m/s^2) is the gravity acceleration; and is the median grain size.

The Shields parameter due to waves () and currents is defined as

.... (eq. 10)

.... (eq. 11)

During high-energy hydrodynamic conditions, ripples can be washed out. According to Soulsby et al. (2012), the effect of wash-out at large current speeds can be included using a criterion given in terms of skin friction Shields parameters as a function of D*. Then, the limit of wash-out is

when .. (eq. 12)

This corresponds to the inception of the sheet flow regime, when most of the sediment transport occurs in a thin layer close to the bed (Camenen and Larson, 2006). Camenen (2009) reviewed some of the expressions proposed and developed an evaluation of sheet flow estimations. Because the expressions are based on empirical equations, they resulted in great variability. The skin-friction sheet flow threshold as a function of D* proposed by Soulsby et al. (2012) is

when .. (eq. 13)

3.4.7.Ripple prediction

Ripple predictors to estimate the bedform characteristics are mostly exclusively focussed on ripple geometry parameters: height and wavelength. These predictors are usually defined for current-generated, wave-generated or combined flow ripples. (Wiberg and Harris, 1994; Soulsby and Whitehouse, 2005; van Rijn, 2007b; Camenen, 2009; Maier and Hay, 2009; Soulsby et al., 2012; Nelson and Voulgaris, 2014).

For instance, Nelson and Voulgaris (2015) developed a 2D model based on Soulsby and Whitehouse (2005) ripple prediction and introducing the Traykovski (2007) spectral model able to predict ripple orientation, shape and slope that improved ripple predictions for waves-dominated and waves influenced by currents conditions. The use of different approaches trying to improve ripple prediction is out of the aims of this study, but it is a topic that deserves further research. Given the available field data and the clear hydrodynamic conditions, the methodology of the theory of equilibrium ripple dimensions of Soulsby et al. (2012) is used here because of its simplicity and because it is based on the comparison of the Shields parameter thresholds obtained with the hydrodynamic measurements. The Shields thresholds are compared with Shields due to waves () leading to wave-generated ripples and with Shields due to currents () leading to current-generated ripples. When waves dominate (), the estimated ripple dimensions grow when the energy increases and decay when the energy decreases, because they are a direct function of the wave orbital velocity. When currents dominate (), current ripples can develop when with constant and maximum bedform dimensions. Under increasing energy, a linear reduction in ripple height is defined between and , and it is assumed that the wavelength is unaffected by wash-out, being equivalent to the maximum value. When currents dominate over waves, ripple dimensions decrease () until they completely wash out, imposing flatbed () (Soulsby et al., 2012). Finally, for waves and currents acting together, this ripple prediction model assumes that only the dominant ripple train of the two is present at any time (Li and Amos, 1998).

3.4.8. Sediment transport rate

The sediment transport rate was estimated following the van Rijn (2007a, 2007b) methodology because of its simplicity for obtaining estimations of the bedload and suspended load sediment transport in coastal flows. The method only requires the basic hydrodynamic parameters (depth, current velocity, wave height, wave period, etc.) and the basic sediment characteristics (d_{50}) (van Rijn, 2007a). In addition, the formula is universal in the sense that it can be applied to the full range of sediment sizes (8-2000 µm) and the full hydrodynamic regimes (including coastal flows).

3.4.9. Suspended sediment concentration

The turbidity time series were used to obtain the suspended sediment concentration at ~1 mab. The data were processed to correct inconsistent values in three steps: (i) checking values larger than the average of the two preceding measurements plus 100; (ii) checking measurements larger than the previous and following values plus 20; and (iii) removing values that meet the two conditions and replacing them with their average.

4. Results

4.1. Waves and near-bottom current time series

The at the tripod location ranged from 0.1 m to maximum values of ~3 m, with several periods of >1 m (Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from

23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.. b). The highest waves (>2 m) occurred mostly during November and early December and represented conditions of moderate wave storms with peak wave periods () of 8 and 12 s. The storms were clearly eastern storms (locally called

“Llevantades”), with only one exception on 24 December, when waves came from the S (Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23

October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.. b). Following the waves, the near-bottom orbital velocity () displayed several peaks >0.4 m/s, mostly between November and early December, and a maximum peak of 0.8 m/s on 16 November (Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.. d).

The current speed measurements at ~1 mab showed periods of intense currents between November and December, similarly to the wave heights (Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from

23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.. c). The maximum speed recorded was ~0.6 m/s on 16 November and 27 December. When current speeds increased over 0.2 m/s, they were always channelized towards the SSE.

4.2.Seabed morphological changes and ripple observations

The surficial bottom sediment at the tripod location on the 13th October 2013 was fine sand with a median sediment grain size (d_{50}) of 210 µm. The sediment was composed with two grain size populations: the 91% of well-sorted fine sand with a mode around 230 µm and the 9% of mud mostly silt (Bottom sediment grain size distribution of the surficial sample (0-1 cm) at the tripod location on the 13th of October of 2013.).

The altimeter was able to measure the topographic variability of the seabed from the beginning of the deployment until 16 November, when the most energetic storm measured occurred (Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.

The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.. e). During this period a settle of ~10 cm was first recorded on 17 October, probably as a consequence of the structure stabilizing (Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. 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The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.. e). The seabed position measurements alternated between steady and oscillating topographic periods (Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16

November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.. e). Seabed oscillations displayed fluctuations of the order of 20 cm, and smaller oscillations of the order of a few centimetres (Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from

23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed. e), the latter related to ripple development periods.

Six periods of ripple formation were identified from the images of the video camera during the first month of deployment (Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) a, Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.

The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed. a). In general, ripples developed during low- to moderate-energy hydrodynamic conditions. They were typically generated by the action of waves and/or currents and their size was well correlated with the flow energy, exhibiting greater dimensions under high-energy conditions and smaller dimensions under low-energy conditions. At the end of each ripple development period, these small bedforms degraded progressively when the energy decreased or increased above the wash-out threshold (Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16

November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.. a, Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and

(e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. 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The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed. a). 2D ripples formed during low-energy hydrodynamic conditions and were associated with waves (~1 m), while 3D ripples formed under slightly higher (but moderate) energy conditions and were associated with waves and currents (Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. 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The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.).

4.3.Ripple classification

Plan view seabed morphologies were distinguished and classified as follows: flat bottom; small undulations; 2D ripples (ripples with rectilinear crests); 3D ripples (ripples with sinuous crests); ripple decay or degradation; and no data, when images were not available or quality was too low to identify any morphology on the seabed (Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.. a, Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed. a). A complete description was obtained using the images recorded with the video camera, the time series of the propagated and direction, current velocity measured at ~1 mab, the seabed topographic variations measured with the altimeter, the measurements of the suspended sediment concentration at ~1 mab and the estimations of near-bottom stresses at the boundary layer.

4.3.1. Undulations

During low-energy hydrodynamic conditions, small undulations were observed lying on the seabed (Example of the undulations observed in the instantaneous images from the video record on 1 November at 19 h.). The small bedforms were not classified as ripple bedforms because they were not sufficiently well developed, showing crests without a clear continuity in length and small dimensions ($<$ 0.5 cm and ~8 cm) (Example of the undulations observed in the instantaneous images from the video record on 1 November at 19 h.). These undulations formed during periods of waves of = 0.5-1 m and low current speed (< 0.1 m/s) (Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from

23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.).

4.3.2.2D ripples

Ripples with a sinuosity index close to one and only one ripple crests direction were classified as 2D ripples ((a) Sinuosity and (b) ripple crest direction box plots of the four periods when different ripples morphologies were observed.). 2D ripples displayed straight crests aligned N-S and well correlated with periods of wave-dominated hydrodynamic conditions (wave ripples) (Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed. and Example of 2D ripple formation observed in the instantaneous images (a) on 27 October at 23 h; (b) benthic community contribution to ripple degradation on 28 October at 19 h). Two periods of 2D ripple development were identified.

2D ripples were first observed on 27 October at 19 h, and at 23 h they were even better developed during a small (< 1 m) eastern storm (Example of 2D ripple formation observed in the instantaneous images (a) on 27 October at 23 h a). The ripples displayed rectilinear N-S-oriented crests, with mean 1.2 cm and 7-

10 cm (0.15) (Example of 2D ripple formation observed in the instantaneous images (a) on 27 October at 23 h a). The analysis of the temporal seabed topographic variation and the ripple crest geometries and positions revealed that they were static, with neither migration nor dynamism. Previous images (26 October) showed the presence of undulations at the beginning of the eastern wave event (~1 m), suggesting that the pre-existing undulations acted as precursors of ripple formation (Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states

observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed. a). Finally, the ripples degraded progressively mainly due to the biological activity of the benthic community (Example of 2D ripple formation observed in the instantaneous images (a) on 27 October at 23 h; (b) benthic community contribution to ripple degradation on 28 October at 19 h b).

A second period of N-S-oriented, straight-crest ripple morphologies with mean 0.5 cm (maximum heights of 1 cm) and 6-8 cm (0.07) formed between 19 and 23 h on 3 November, when eastern waves increased to ~1 m (Example of 2D ripple formation observed in the instantaneous images (a) on 27 October at 23 h; (b) benthic community contribution to ripple degradation on 28 October at 19 h; and (c) on 4 November at 3 h. c). The previous seabed state was “flatbed” with some roughness resulting from the biological activity, but no undulations were previously observed. The 2D ripples also remained static on the seabed, with neither dynamism nor migration.

4.3.3. Mixed 2D/3D ripples

Mixed 2D/3D ripples were characterized as dynamic bedforms that changed their arrangement from sinuous to rectilinear crests with larger dimensions than those of the 2D ripples described above ((a) Sinuosity and (b) ripple crest direction box plots of the four periods when different ripples morphologies were observed., Example of ripple formation under current-dominated conditions observed in the instantaneous images on (a) 4 November at 19 h; (b) 4 November at 23 h; (c) 5 November at 3 h; (d) 5 November at 19 h; (e) 6 November at 3 h; and (f) 6 November at 19 h.). 2D ripples presented low sinuosity while 3D ripples morphologies resulted in sinuosity indexes further from one and crestlines directions with a wide variability ((a) Sinuosity and (b) ripple crest direction box plots of the four periods when different ripples morphologies were observed.). These ripples occurred during current-dominated hydrodynamic conditions (current ripples) and were observed during three different periods in November

(Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from

23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.). For example, a rippled bed with sinuous crests and small dimensions developed on 4 November at 19 h under high-speed currents (>0.3 m/s), just after the

previous wave ripple formation described above (Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from

23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed. a; Example of ripple formation under current-dominated conditions observed in the instantaneous images on (a) 4 November at 19 h; (b) 4 November at 23 h; (c) 5 November at 3 h a). The size of ripples increased/decreased following the current speeds (Example of ripple formation under current-dominated conditions observed in the instantaneous images on (a) 4 November at 19 h; (b) 4 November at 23 h; (c) 5 November at 3 h; (d) 5 November at 19 h a, b, c). Moderate currents (0.2-0.3 m/s) flowing towards the S led to modification of the ripple morphologies from 3D to 2D (crests oriented W-E), completely removing the residual ripple morphologies from the previous wave ripple period (Example of ripple formation under current-dominated conditions observed

in the instantaneous images on (a) 4 November at 19 h; (b) 4 November at 23 h; (c) 5 November at 3 h; (d) 5 November at 19 h; (e) 6 November at 3 h; and (f) 6 November at 19 h. d, e). Finally, the ripples degraded, displaying rounded crests and poorly-defined shapes under lower current speed (Example of ripple formation under current-dominated conditions observed in the instantaneous images on (a) 4 November at 19 h; (b) 4 November at 23 h; (c) 5 November at 3 h; (d) 5 November at 19 h; (e) 6 November at 3 h; and (f) 6 November at 19 h. f). The mean ripple height was estimated at around 0.8 cm (maximum >1.5 cm) and the wavelength () around 10-15 cm (0.05-0.15) for the whole period of appearance. The ripples migrated towards the SSE at rates of 6-10 cm/h.

4.3.4.3D ripples

3D ripples displayed sinuous crests morphologies resulting in sinuosity indexes further from one and ripples directions diverged ((a) Sinuosity and (b) ripple crest direction box plots of the four periods when different ripples morphologies were observed.). 3D ripples had larger dimensions than the 2D ripples and were formed under wave-current hydrodynamic conditions (Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.). They migrated towards the S accordingly with the current flow.

3D ripple morphologies were observed for the first time on 29 October at 7 h (Example of 3D ripple formation under wave-current-dominated conditions observed in the instantaneous images on (a) 29 October at 7 h; (b) 29 October at 15 h; (c) 29 October at 23 h; (d) 30 October at 3 h; (e) 31 October at 3 h a) and lasted until 31 October, when the ripples started to decline (Example of 3D ripple formation under wave-current-dominated conditions observed in the instantaneous images on (a) 29 October at 7 h; (b) 29

October at 15 h; (c) 29 October at 23 h; (d) 30 October at 3 h; (e) 31 October at 3 h; and (f) 31 October at 7 h. f). Previous to the development of 3D ripples, the seabed configuration displayed slight roughness elements: small undulations corresponding to the residual morphologies from the former 2D ripples (Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed. a). The 3D ripples progressively readapted their morphologies and sizes by growing and displaying better-defined crests as a result of the increasing currents and wave heights (e.g. Example of 3D ripple formation under wave-current-dominated conditions observed in the instantaneous images on (a) 29 October at 7 h; (b) 29 October at 15 h; (c) 29 October at 23 h; (d) 30 October at 3 h; (e) 31 October at 3 h; and (f) 31 October at 7 h. c-e). However, they also degraded slightly during the second and highest current speed peak (v ~0.5 m/s) and wave heights (= 1.2 m) of the event on 30 October (Example of 3D ripple formation under wave-current-dominated conditions observed in the instantaneous images on (a) 29 October at 7 h; (b) 29 October at 15 h; (c) 29 October at 23 h; (d) 30 October at 3 h; (e) 31 October at 3 h; and (f) 31 October at 7 h. d). Finally, the ripples degraded progressively at the end of this wave-current event (Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed. a, Example of 3D ripple formation under wave-current-dominated conditions observed in the instantaneous images on (a) 29 October at 7 h; (b) 29 October at 15 h; (c) 29 October at 23 h; (d) 30 October at 3 h; (e) 31 October at 3 h; and (f) 31 October at 7 h. f). Ripple mean height was 1.9 cm, with maximum ripple height values of ~2.2 cm and 7-20 cm (0.10-0.25). These ripples were highly dynamic, with migration rates of 5-13 cm/h towards the SSE.

Video-records during these events revealed the presence of fishes swimming against the current flow (perpendicular to the ripple crest arrangement) (e.g. Example of 3D ripple formation under wave-current-dominated conditions observed in the instantaneous images on (a) 29 October at 7 h; (b) 29 October at 15 h; (c) 29 October at 23 h; (d) 30 October at 3 h; (e) 31 October at 3 h b) and the oscillatory movement (parallel to ripple crests) of sand and shells, presumably induced by the eastern waves (e.g. in the video of the instantaneous image Example of 3D ripple formation under wave-current-dominated conditions observed in the instantaneous images on (a) 29 October at 7 h; (b) 29 October at 15 h; (c) 29 October at 23 h; (d) 30 October at 3 h; (e) 31 October at 3 h d).

4.4.Seabed mobility

The hydrodynamic forcing conditions acting on the seabed during the study period were characterized by estimating the Shields parameter generated by waves and currents (Time series from October to December of (a) turbidity in normalized turbidity units (NTU) measured at ~1 mab; (b) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (c) b). The maximum Shields parameter due to waves () was reached on 16 November, and after this event a few peaks of > 0.2 occurred. Current Shields parameter peaks ranged between 0.1 and 0.2, coinciding with the highest peaks in the near-bottom current speeds (Time series from October to December of (a) turbidity in normalized turbidity units (NTU) measured at ~1 mab; (b) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (c) b). The estimated Shields parameter thresholds of motion, wash-out and sheet flow conditions were 0.05, 0.19 and 0.26, respectively (Shields parameter thresholds for critical, wash-out and sheet flow conditions obtained with different). The comparison between the Shields parameter due to waves and these thresholds suggested that ~17.2% of the time , 1% of the time and 0.4% of the time . The remaining 81.4% of time the hydrodynamics induced by waves was below the threshold of sediment motion. The Shields parameter due to currents () exceeded the theoretical critical threshold of grain motion ~12.9% of the time, but it was always below the threshold of wash-out conditions (Time series from October to December of (a) turbidity in normalized turbidity units (NTU) measured at ~1 mab; (b) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (c) b). In summary, considering both wave and current Shields parameters, critical conditions for grain movement were exceeded during 24% of the time and wash-out and sheet flow were only reached during 1% and 0.4% of the time, respectively, under high-energy waves. The remaining 74.6% of the time conditions were below the critical threshold of motion.

Table II. Shields parameter thresholds for critical, wash-out and sheet flow conditions obtained with different approaches.

Author(s)					**hydrodynamic conditions defined method**
Nielsen (1981)	-	-	1	-	oscillatory flow
Li and Amos (1999)	-	-	0.2	-	steady and oscillatory combined
Kleinhans (2005)	-	-	[0-0.56]	-	steady and oscillatory combined
Soulsby and Whitehouse (2005)	-	-	-	~2000	oscillatory flow
Soulsby et al. (2012)	0.05	0.19	0.26	-	steady and oscillatory combined

4.5. Sediment transport rate

Most of the estimated near-bottom sediment transport occurred in short pulses during severe storms (Time series from October to December of (a) turbidity in normalized turbidity units (NTU) measured at ~1 mab; (b) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (c) total sediment transport rate (), suspended sediment transport rate () and bedload sediment transport rate (); (d) ripple wavelengths in cm from observations (red dots) and obtained with the ripple predictor of Soulsby et al. (2012) (black dots); and (e) ripple wavelength in cm from observations and obtained with the ripple predictor of Soulsby et al. (2012) (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical threshold, and coloured shaded areas indicate the periods of ripple development detailed in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.. c). Peaks of sediment transport ranging from 100 to 400 g/s/m occurred from mid-November to early December, with the maximum on 16 November (Time series from October to December of (a) turbidity in normalized turbidity units (NTU) measured at ~1 mab; (b) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (c) total sediment transport rate (), suspended sediment transport rate () and bedload sediment transport rate (); (d) ripple wavelengths in cm from observations (red dots) and obtained with the ripple predictor of Soulsby et al. (2012) (black dots); and (e) ripple wavelength in cm from observations and obtained with the ripple predictor of Soulsby et al. (2012) (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical threshold, and coloured shaded areas indicate the periods of ripple development detailed in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.. c). Several smaller peaks of ~20 g/s/m were also estimated under moderate conditions (e.g. on 26 November and on 21 December) (Time series from October to December of (a) turbidity in normalized turbidity units (NTU) measured at ~1 mab; (b) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (c) total sediment transport rate (), suspended sediment transport rate () and bedload sediment transport rate (); (d) ripple wavelengths in cm from observations (red dots) and obtained with the ripple predictor of Soulsby et al. (2012) (black dots); and (e) ripple wavelength in cm from observations and obtained with the ripple predictor of Soulsby et al. (2012) (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical threshold, and coloured shaded areas indicate the periods of ripple development detailed in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.. c). In general, the sediment transport rate was high during events when waves dominated, although most of them were wave-current events (Time series from October to December of (a) turbidity in normalized turbidity units (NTU) measured at ~1 mab; (b) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (c) total sediment transport rate (), suspended sediment transport rate () and bedload sediment transport rate (); (d) ripple wavelengths in cm from observations (red dots) and obtained with the ripple predictor of Soulsby et al. (2012) (black dots); and (e) ripple wavelength in cm from observations and obtained with the ripple predictor of Soulsby et al. (2012) (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical threshold, and coloured shaded areas indicate the periods of ripple development detailed in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.. c). Estimations suggested that the sediment transport was widely dominated by suspended load rather than bedload (92% and 8%, respectively), in agreement with observations of suspended sediment concentration (inferred from turbidity measurements), which displayed a strong relation to high-energy wave-current conditions (Time series from October to December of (a) turbidity in normalized turbidity units (NTU) measured at ~1 mab; (b) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (c) total sediment transport rate (), suspended sediment transport rate () and bedload sediment transport rate (); (d) ripple wavelengths in cm from observations (red dots) and obtained with the ripple predictor of Soulsby et al. (2012) (black dots); and (e) ripple wavelength in cm from observations and obtained with the ripple predictor of Soulsby et al. (2012) (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical threshold, and coloured shaded areas indicate the periods of ripple development detailed in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.. a). In general, the measured turbidity peaks were well correlated with periods when the Shields parameter exceeded the critical threshold (grey-shaded areas in Time series from October to December of (a) turbidity in normalized turbidity units (NTU) measured at ~1 mab; (b) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (c) total sediment transport rate (), suspended sediment transport rate () and bedload sediment transport rate (); (d) ripple wavelengths in cm from observations (red dots) and obtained with the ripple predictor of Soulsby et al. (2012) (black dots); and (e) ripple wavelength in cm from observations and obtained with the ripple predictor of Soulsby et al. (2012) (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical threshold, and coloured shaded areas indicate the periods of ripple development detailed in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and

(e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.. a). During periods of 3D ripple development, 83% of the sediment transport was attributed to suspended load and the remaining 17% to bedload.

5. Discussion

5.1. Ripple occurrence and prediction

Video observations of ripples on the Ebro Delta are biased, being limited to low and moderate hydrodynamic conditions because during storm events the high suspended sediment concentration prevents seabed video observations. From low to moderate energy, the observations suggest a transition from undulations on the seabed to 2D wave ripples (~1 m), current-dominated 2D/3D ripples, and finally the largest wave-current 3D ripples. Ripple decay also occurred when the hydrodynamic regime increased the energy (wash-out), or because of biological activity (mostly of the benthic community) that progressively degraded the bedforms (e.g. Example of 2D ripple formation observed in the instantaneous images (a) on 27 October at 23 h; (b) benthic community contribution to ripple degradation on 28 October at 19 h; and (c) on 4 November at 3 h. b), as observed and suggested previously by Guillén et al. (2008) and Soulsby et al. (2012).

Most ripple formation observations at the study site coincide with periods when the Shields parameter exceeded the threshold condition for initiation of sediment motion (0.05) (Detail from 23 October to 16 November of time series of (a) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (b) total sediment transport rate (qt), suspended sediment transport rate (qs) and bedload sediment transport rate (qb); (c) ripple wavelengths in cm from observations (red dots) and obtained with the Soulsby et al (2012) ripple predictor (black dots); and (d) ripple height in cm from observations and obtained with the Soulsby et al (2012) ripple predictor (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical Shields parameter.). However, undulations can be formed on the seabed below the critical Shields limit under small waves (0.5-1 m) and weak currents (v <0.1 m/s) (Detail from 23 October to 16 November of time series of (a) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (b) total sediment transport rate (qt), suspended sediment transport rate (qs) and bedload sediment transport rate (qb); (c) ripple wavelengths in cm from observations (red dots) and obtained with the Soulsby et al (2012) ripple predictor (black dots); and (d) ripple height in cm from observations and obtained with the Soulsby et al (2012) ripple predictor (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical Shields parameter., Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... 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The coloured shaded areas indicate the ripple morphologies observed.. and Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.). These undulations (< 5 mm) are precursors of 2D ripples if the waves remain constant or increase slightly, as observed on 26 October (Detail from 23 October to 16 November of time series of (a) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (b) total sediment transport rate (qt), suspended sediment transport rate (qs) and bedload sediment transport rate (qb); (c) ripple wavelengths in cm from observations (red dots) and obtained with the Soulsby et al (2012) ripple predictor (black dots); and (d) ripple height in cm from observations and obtained with the Soulsby et al (2012) ripple predictor (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical Shields parameter.). The transition from a plane bed to well-developed ripples through the formation of smaller bedforms (<3 mm) as precursors was previously observed with high-speed flows (> 0.65 m/s) (Reesink and Bridge, 2007), although this transition seems to occur during low-energy wave conditions in the Ebro. The shortage of available records during higher-energy periods prevents a detailed comparison of theoretical wash-out and sheet flow thresholds with observations. The 3D ripple decay occurred during a wave-current peak (on 30 October and suggests the initiation of ripple wash-out with 0.1, when the measured current speed was above 0.55 m/s (Detail from 23 October to 16 November of time series of (a) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (b) total sediment transport rate (qt), suspended sediment transport rate (qs) and bedload sediment transport rate (qb); (c) ripple wavelengths in cm from observations (red dots) and obtained with the Soulsby et al (2012) ripple predictor (black dots); and (d) ripple height in cm from observations and obtained with the Soulsby et al (2012) ripple predictor (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical Shields parameter.).

The application of the ripple predictor approach based on the critical Shields parameter (Soulsby et al., 2012) roughly fits with the appearance of ripples (Detail from 23 October to 16 November of time series of (a) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (b) total sediment transport rate (qt), suspended sediment transport rate (qs) and bedload sediment transport rate (qb); (c) ripple wavelengths in cm from observations (red dots) and obtained with the Soulsby et al (2012) ripple predictor (black dots); and (d) ripple height in cm from observations and obtained with the Soulsby et al (2012) ripple predictor (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical Shields parameter. a). However, undulations and 2D ripples were also observed below or near the theoretical threshold of initiation of sediment motion (Detail from 23 October to 16 November of time series of (a) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (b) total sediment transport rate (qt), suspended sediment transport rate (qs) and bedload sediment transport rate (qb); (c) ripple wavelengths in cm from observations (red dots) and obtained with the Soulsby et al (2012) ripple predictor (black dots); and (d) ripple height in cm from observations and obtained with the Soulsby et al (2012) ripple predictor (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical Shields parameter.). The ripple predictor slightly underestimated ripple wavelength (Detail from 23 October to 16 November of time series of (a) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (b) total sediment transport rate (qt), suspended sediment transport rate (qs) and bedload sediment transport rate (qb); (c) ripple wavelengths in cm from observations (red dots) and obtained with the Soulsby et al (2012) ripple predictor (black dots); and (d) ripple height in cm from observations and obtained with the Soulsby et al (2012) ripple predictor (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical Shields parameter. c), while it underestimated ripple heights under wave-dominated conditions and overestimated them under current-dominated conditions (Detail from 23 October to 16 November of time series of (a) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (b) total sediment transport rate (qt), suspended sediment transport rate (qs) and bedload sediment transport rate (qb); (c) ripple wavelengths in cm from observations (red dots) and obtained with the Soulsby et al (2012) ripple predictor (black dots); and (d) ripple height in cm from observations and obtained with the Soulsby et al (2012) ripple predictor (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical Shields parameter. d). However, in general the dimensions differences were low in the order of a few centimetres for the wavelength and millimetres for ripple height. In addition, the ripple predictor failed under mixed wave-current conditions, probably because of the assumption that only one of the two mechanisms (waves or currents) is the dominant one and because the method is not well defined for 3D ripples. The ripple predictor model improves considerably when the values of Shields parameters of ripples appearance, degradation and wash-out extracted from the observations are applied instead of the theoretical thresholds of critical, wash-out and sheet flow, respectively. . Thus, though the approach of Soulsby et al. (2012) has been shown to yield one of the best predictions for ripple characteristics, it still suffers inaccuracies because of the estimation of the Shields parameter, it fails to account properly for the inception of sheet flow, and it largely overestimates the results when ripples are washed out (Camenen, 2009). Ripples are usually assumed to be non-equilibrium state features in a field that show rapid (at times even ephemeral) variability in their formation and dynamism. Therefore, ripple prediction is still working in progress and should be improved by adjusting field observations and modelling because prediction of ripple appearance and dimensions is highly valuable in the estimation of bed roughness, a decisive parameter in boundary layer processes.

5.2.Ripples and sand ridge dynamics

Ripples at the study site lay superimposed on the extreme and deepest part of the SE face of a symmetric sand ridge. Only mixed 2D/3D and 3D ripples were dynamic, with changing morphologies and arrangements adapting to the hydrodynamics and migrating towards the SE accordingly with the current flow direction. However, 2D wave ripples remained fixed and stable. Though wave asymmetry can be an additional mechanism of ripple migration (Traykovski et al., 1999), wave ripples were static in the Ebro area, probably because near-bottom wave velocities at the study site were symmetric or very slightly asymmetric during low- and moderate-energy periods of wave ripple observations.

Both ripples and sand ridges migrate towards the SSE as a consequence of wind-induced currents and it is feasible that ripples make some contribution to sand ridge dynamics. Generally, large-scale bedforms tend to move more slowly than small-scale features (Venditti et al., 2005). The migrating superimposed bedforms overtake the larger ones and avalanche on the lee side of them, contributing to the migration of the host bedforms (Reesink and Bridge, 2009). The scale of sediment transport involved in the migration of superimposed and host bedforms differs, although it can be nearly identical if size and migration rates of the two are proportional, i.e. ripples move 10 times faster and are 0.1 times the size of the host bedform (Venditti et al., 2005).

At the study site, the highest sediment transport occurred when the Shields parameter exceeded the theoretical wash-out threshold, which was in the absence of ripples. In the presence of 2D/3D ripples (between the critical and wash-out theoretical thresholds), the sediment transport was one order of magnitude lower than the highest peaks (Time series from October to December of (a) turbidity in normalized turbidity units (NTU) measured at ~1 mab; (b) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (c) total sediment transport rate (), suspended sediment transport rate () and bedload sediment transport rate (); (d) ripple wavelengths in cm from observations (red dots) and obtained with the ripple predictor of Soulsby et al. (2012) (black dots); and (e) ripple wavelength in cm from observations and obtained with the ripple predictor of Soulsby et al. (2012) (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical threshold, and coloured shaded areas indicate the periods of ripple development detailed in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed..), while for Shields values slightly above or below the critical value of sediment motion, when undulations and the 2D stationary wave ripples developed, the estimated sediment transport was almost null (Detail from 23 October to 16 November of time series of (a) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (b) total sediment transport rate (qt), suspended sediment transport rate (qs) and bedload sediment transport rate (qb); (c) ripple wavelengths in cm from observations (red dots) and obtained with the Soulsby et al (2012) ripple predictor (black dots); and (d) ripple height in cm from observations and obtained with the Soulsby et al (2012) ripple predictor (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical Shields parameter.). In presence of 3D ripples (29 to 31 October) a peak of total sediment transport was estimated, with 83% due to suspended load and the remaining 17% due to bedload (Detail from 23 October to 16 November of time series of (a) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (b) total sediment transport rate (qt), suspended sediment transport rate (qs) and bedload sediment transport rate (qb); (c) ripple wavelengths in cm from observations (red dots) and obtained with the Soulsby et al (2012) ripple predictor (black dots); and (d) ripple height in cm from observations and obtained with the Soulsby et al (2012) ripple predictor (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical Shields parameter. b). Therefore, the bedload transport could have partially occurred in the form of 3D ripple migration.

Ripple migration was observed during current conditions and combined wave and current conditions when flows were lower than 0.55 m/s and . The instantaneous ripple migration rates estimated from observations were ~10 cm/h. The extrapolation of ripple migration rates to periods when provides a rough estimation of the mean ripple migration of 1.3 cm/h during the study period, which should be lower over the year because of the low-energy summer period. Moreover, the annual sand ridge migration rate was ~10 m/y (Guerrero et al., 2018), representing a mean rate of 0.11 cm/h. A rough comparison between ripple/sand ridge mean size (0.015 /1.5 m) and migration rates (1.3 /0.11 cm/h) suggests, according to the relationships established by Venditti et al. (2005), that the sediment transport associated with ripple migration could be one order of magnitude lower than the total transport involved in sand ridge migration. This would be a subordinate but non-negligible amount of the bedload sediment transport associated with bedform migration. While most of the sediment transport and sand ridge migration would occur under sheet flow conditions when ripples were washed out during high-energy episodes, sand ridge migration would also occur during low- to moderate-energy hydrodynamic conditions.

In a more general perspective, the contribution of small bedforms to the growth of larger bedforms and, after formation, the presence of ephemeral small bedforms migrating on the backs of the larger ones have been described (Allen, 1982; Gomez et al., 1989; Venditti et al., 2005; Reesink and Bridge, 2009, 2007). The contribution of small bedforms as ripples during low- to moderate-energy hydrodynamics can help to understand the formation, dynamics and maintenance of large bedforms with no need to resort exclusively to high-energy conditions. For instance, it was hypothesized that low- to moderate-energy processes could explain the maintenance of the morphology of large-scale sand ridges on the continental shelf (Simarro et al., 2015). On the shoreface of the Ebro Delta, the sand ridge could also be dynamic during moderate current episodes because of ripple migration. If this is the case, our vision of large bedforms that remain static during most of the time and are only active during high-energy or extreme conditions should be changed.

6. Conclusions

Seabed morphological observations showed that the presence of ripples is the most usual seabed configuration on the Ebro Delta shoreface during low and moderate hydrodynamic conditions. Four types of small-scale bedforms were identified, from values just below the critical threshold of sediment motion to wash-out conditions: (i) small undulations with 0.5 cm and 8 cm, formed as precursors of wave ripples when the Shields parameter was just below the critical level; (ii) 2D wave ripples with 1.2 cm and 7-10 cm; (iii) mixed 2D/3D current-dominated ripples with 0.8 cm (max. ~1.5 cm) and 10-15 cm; and (iv) 3D wave-current ripples with 1.9 cm (max. ~2.2 cm) and 7-20 cm. Ripple degradation occurred when the hydrodynamic regime increased the energy (wash-out conditions), or under low-energy hydrodynamic conditions, when ripples progressively decayed mainly as a consequence of biological activity by the benthic community, which flattened the relict ripples.

The ripple predictor method roughly fits with the appearance of ripples but fails to predict ripple dimensions, especially during wave-current conditions. The development of small seabed undulations below the theoretical threshold of grain movement is a major concern in ripple and sediment transport prediction, suggesting that the estimated thresholds are progressive ranges rather than abrupt changes.

Most sediment transport occurred during severe storms and under sheet flow conditions when ripples were washed out. In presence of ripples, only during the development of 3D wave-current ripples was significant sediment transport estimated. Observations of the suspended sediment and ripple development also demonstrated that under low- to moderate-energy conditions 2D ripples (wave ripples) formed and remained static features (probably because of the wave orbital velocity symmetry). However, when the energy induced by eastern waves increased, the ripples were washed out and large amounts of fine sand and mud were resuspended and available to be transported towards the NW-W.

Mean ripple migration rates were ~10 cm/h during only current and wave-current events. Migration of 3D ripples was dominated by the wind-induced current towards the SSE, which is the same direction as that of sand ridge migration on the Ebro shoreface. Accordingly, it was hypothesized that part of the sand ridge migration could be associated with ripple migration. Rough estimations suggest that the input of ripples to the migration of sand ridges could be no more than one order of magnitude lower than the total transport involved in sand ridge migration. However, this subordinate amount of sediment transport is representative because it suggests that large-scale bedforms could be dynamic during low- to moderate-energy processes and not only during high-energy or extreme conditions.

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Figures caption

Fig. 1.(a) Ebro Delta location. (b) Subaerial Ebro Delta shaded-relief and bathymetric contours offshore with location of the sand ridge field in grey. Location of tripod, sediment sample and the Buda Island meteorological station.

Fig. 2.Image of the tripod structure during the deployment manoeuvres on the deck of the ship on 13 October 2013. Numbers indicate the position of the instruments used here: (1) video camera; (2) currentmeter; and (3) altimeter.

Fig. 3.Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013

shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from

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Fig. 4.Bottom sediment grain size distribution of the surficial sample (0-1 cm) at the tripod location on the 13th of October of 2013.

Fig. 5.Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at $\sim$1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at $\sim$1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at $\sim$1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at $\sim$1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from

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Fig. 6.Example of the undulations observed in the instantaneous images from the video record on 1 November at 19 h.

Fig. 7.(a) Sinuosity and (b) ripple crest direction box plots of the four periods when different ripples morphologies were observed.

Fig. 8.Example of 2D ripple formation observed in the instantaneous images (a) on 27 October at 23 h; (b) benthic community contribution to ripple degradation on 28 October at 19 h; and (c) on 4 November at 3 h.

Fig. 9.Example of ripple formation under current-dominated conditions observed in the instantaneous images on (a) 4 November at 19 h; (b) 4 November at 23 h; (c) 5 November at 3 h; (d) 5 November at 19 h; (e) 6 November at 3 h; and (f) 6 November at 19 h.

Fig. 10.Example of 3D ripple formation under wave-current-dominated conditions observed in the instantaneous images on (a) 29 October at 7 h; (b) 29 October at 15 h; (c) 29 October at 23 h; (d) 30 October at 3 h; (e) 31 October at 3 h; and (f) 31 October at 7 h.

Fig. 11.Time series from October to December of (a) turbidity in normalized turbidity units (NTU) measured at ~1 mab; (b) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (c) total sediment transport rate (), suspended sediment transport rate () and bedload sediment transport rate (); (d) ripple wavelengths in cm from observations (red dots) and obtained with the ripple predictor of Soulsby et al. (2012) (black dots); and (e) ripple wavelength in cm from observations and obtained with the ripple predictor of Soulsby et al. (2012) (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical threshold, and coloured shaded areas indicate the periods of ripple

development detailed in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from

23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed..

Fig. 12.Detail from 23 October to 16 November of time series of (a) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (b) total sediment transport rate (q_t), suspended sediment transport rate (q_s) and bedload sediment transport rate (q_b); (c) ripple wavelengths in cm from observations (red dots) and obtained with the Soulsby et al (2012) ripple predictor (black dots); and (d) ripple height in cm from observations and obtained with the Soulsby et al

(2012) ripple predictor (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical Shields parameter.